STRAIN RATE SENSITIVITY OF GRAPHITE/POLYMER LAMINATE COMPOSITES.

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Abstract. Strain rate sensitivities of Graphite/Epoxy and Graphite/Peek laminate composites are investigated by measuring their stress-strain response at strain rates of 0.001/s, 0.1/s, and 400/s. Tension specimens of the composite laminates are fabricated in a dog-bone shape. Stress-strain data at quasi-static rates of 0.001/s and 0.1/s are obtained using a servohydraulic test system. High strain rate data are produced with a Direct Tension Split Hopkinson Bar (DTSHB). A tensile stress pulse is generated in the DTSHB by impacting a stopper flange at the end of the incident bar with an aluminum/polymeric tube launched around the incident bar. The failure (flow) tensile stress of Graphite/Epoxy increases from 240 MPa to 280±10 MPa (ε = 0.06) when the strain rate is raised from 0.001/s to 400/s. For Graphite/Peek, failure (flow) tension stress increases from 175 MPa at a strain rate of 0.001/s to 270±20 MPa at a strain rate of 400/s.

INTRODUCTION

Fiber-reinforced laminate composites (glass-epoxy, graphite-epoxy) and polymers are now finding increased use in a variety of load bearing components in aircraft and automobiles. Often during their normal service life these components are subjected to large strains over a short period of time. Examples of such events include foreign object impact, automotive crashes, and accidental tool drops. There is a continuing debate as to the extent of the strain rate sensitivity of these materials. A number of investigators have reported an increase in the strain rate sensitivity of fiber-reinforced composites and polymers at high strain rate (1-6). Constitutive equations-of-state relating peak (yield) stress with strain rate for these materials are needed to analytically or numerically simulate the structural response of various components to impact loading. The development of the constitutive equation-of-state for composites is a challenging task due to the strong directional dependence (anisotropy) of the material system.

The objective of this paper is to present the tension stress-strain data on graphite fiber/epoxy [AS4/3501-6] and graphite fiber /peek [AS4/APC2] laminate systems fabricated in the [+45/-45]2s configuration at strain rates of 0.001/s, 0.1/s, and 400/s. Low strain rate (quasi-static) stress-strain data were obtained using a Servohydraulic Test System at the WPAFB Materials Laboratory (7). A direct tension split Hopkinson bar (DTSHB) was fabricated to perform high strain rate tests on the laminate composite specimens configured in the dog-bone shape. In order to gain confidence with the new DTSHB, stress-strain data on 6061-T6 aluminum and titanium 6-4 at a strain rate of 10^3/s were generated and compared against the data obtained in our laboratory using conventional SHB and the published data (8).
EXPERIMENTAL CONFIGURATION

Quasi-static Tests

Quasi-static tests were performed at strain rates of 0.001/s and 0.100 /s using a Servohydraulic Test System. A strain gauge was glued to the gauge section of the specimen to corroborate magnitudes of tensile strains (up to 2%) determined from the strain gauge and machine displacement.

Direct Tension Split Hopkinson Bar

The incident and transmitter bars of the DTSHB are made of 25.4-mm diameter aluminum 7075. Two strain gages (1000 Ω) are mounted on each bar 48-inches away from the specimen to monitor strains in the pressure bars. The tensile loading wave is generated by the impact of the striker tube on to the rigid stopper mechanically attached to the end of the incident bar. This stress pulse subjects the specimen to tensile loading. A portion of this incident tensile strain pulse, \( \varepsilon_i \), is transmitted through the specimen \( \varepsilon_t \) and the remainder is reflected back in the incident bar \( \varepsilon_r \). The amplitude of the incident, reflected, and transmitted pulses are recorded by the strain gages. Using the recorded strains, the stress \( \sigma \), strain \( \varepsilon \) and strain rate \( \dot{\varepsilon} \) in the specimen are determined using the following Equations.\(^{8}\)

\[
\sigma(t) = E \frac{A_b}{A_s} \varepsilon_i(t) \quad (1)
\]

\[
\dot{\varepsilon}(t) = \frac{2 \cdot C_o}{L} \varepsilon_i(t) \quad (2)
\]

\[
\varepsilon(t) = \frac{2 \cdot C_o}{L} \int_0^t \varepsilon_i(t) \, dt \quad (3)
\]

where \( A_b \) and \( A_s \) are the cross-sectional area of the pressure bar and the specimen in the gauge section, respectively, and \( L \) is the gauge length of the specimen. \( E \) and \( C_o \) are the Young’s modulus and bar wave velocity, respectively, of bar material. The stress, strain, and strain rate are the average values, and are determined by assuming a uniform uniaxial stress-state condition.

RESULTS AND DISCUSSION

Quasi-static Stress-Strain Data

Typical true stress-strain data on a graphite/epoxy specimen at a strain rate of 0.1/s, shown in Figure 1, demonstrates good agreement between the strains obtained from the specimen strain gauge and those calculated from machine displacement. True stress-strain data on graphite/epoxy and graphite/peek specimens at strain rates of 0.001/s and 0.1/s are shown in Figures 2 and 3. Failure stress for graphite/epoxy specimens corresponding to 0.06 strain at quasi-static strain

Gauge length, width, and nominal thickness of the graphite/epoxy and graphite/peek tensile specimens are 12.7-mm, 7.62-mm, and 1-mm, respectively. Specimens are placed in specially designed grips, which are screwed into the threaded incident and transmitter aluminum bars. A 0.5-m long aluminum tube is launched around the incident bar and the impact of the aluminum tube against the aluminum anvil (rigidly attached to the end of the incident bar) generates a tensile pulse. Incident tensile reflected, and transmitted strain pulses are recorded on Nicolet 320A oscilloscope. These measured data are analyzed using Equations (1) to (3) to determine tensile stress-strain response of graphite composites.

FIGURE 1. Quasistatic Stress-strain curves for graphite/epoxy.
rates is about 240 MPa, whereas for graphite/peek specimen failure stress is 175 MPa. Strains to failure for graphite/epoxy and graphite/peek are 11% and 5.5%, respectively.

![Graphite/Epoxy](image)

**FIGURE 2.** Quasistatic stress-strain curves for graphite/epoxy.

![Graphite/Peek](image)

**FIGURE 3.** Quasistatic stress-strain curves for graphite/peek.

**High Strain Rate Stress-Strain Data**

Specimens of Graphite/epoxy and graphite/peek were tested at a strain rate of 400/s. A total of 6 tests were performed at the two strain rates with three replications at each test condition. True stress-strain data for graphite/epoxy at a strain rate of 400/s are shown in Figure 4. Since the failure strain for graphite/epoxy specimens at this strain rate is 6%, we compare the failure stresses at low and high strain rates corresponding to strain of 6%. Failure stress of graphite/epoxy at a strain rate of 400/s ($\varepsilon=0.06$) is 280±10 MPa, which is about 10% higher than that at low strain rates of 0.001/s and 0.1/s. Failure strain for graphite/epoxy is about 6%, significantly lower than the failure strain of about 11% at low strain rates. A similar increase in the failure stress of graphite fiber/epoxy composite with strain rate was reported by Welsh and Harding (4). Their stress-strain data for graphite fiber reinforced plastic shows an increase in failure stress from about 300 MPa at a strain rate of $10^4$/s to about 400 MPa at a strain rate of 700/s.

Stress-strain data for graphite/peek at a strain rate of 400/s are shown in Figure 5. The increase in failure stress with strain rate is more pronounced in graphite/peek compared to that in graphite/epoxy. Failure stress increases by 70% as the strain rate increases from 0.001/s to 400/s. These results on the extent of strain rate sensitivity in graphite/polymer composites agree with those reported by Harding (3) and Chou et al. (6) on strain rate sensitivity of polymer based composites and polymers.

![Graphite/Epoxy](image)

**FIGURE 4.** Stress-strain curve for graphite/epoxy at 400/s.
CONCLUSIONS

We have fabricated a working direct tension split Hopkinson bar capable of characterizing tensile behavior of laminate composites and other materials (plastics and alloys) available only in the sheet stock, at high strain rates in the range of 200-2000/s. Stress-strain data on specimens of graphite/epoxy [AS4/Epoxy] and graphite/peek [AS4/Peek] laminate systems fabricated in the [+45/-45]_2s configuration show that both types of composites are significantly strain rate sensitive in the strain rate regime from 0.001/s to 400/s.

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REFERENCES


FIGURE 5. Stress-strain curve for graphite/peek at 400/s